Journal of the International Neuropsychological Society (2018), **24**, 476–485.

doi:10.1017/S1355617717001321

On-Field Signs Predict Future Acute Symptoms After Sport-Related Concussion: A Structural Equation Modeling Study

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(Received June 26, 2017; Final Revision November 20, 2017; Accepted November 21, 2017; First Published Online January 8, 2018)

Abstract

Objectives: This study investigated the relationship between on-field, objective signs immediately following sport-related concussion and self-reported symptom endorsement within 1 day post injury. **Methods:** A retrospective case series of 237 concussed high school athletes was performed. On-field signs were evaluated immediately post injury. Self-reported symptoms (2 clusters) were collected within 1 day post injury. A two-step structural equation model and follow-up bivariate regression analyses of significant on-field signs and symptom clusters were performed. **Results**: Signs of immediate memory, $\beta = 0.20$, $p = .04$, and postural instability, $\beta = 0.19$, $p < .01$, significantly predicted a greater likelihood of endorsing the cognitive-migraine-fatigue symptom cluster within 1 day post injury. Regarding signs correlated with specific symptoms, immediate memory was associated with symptoms of trouble remembering, $\chi^2 = 37.92$, $p < .001$, odds ratio (OR) = 3.89 (95% confidence interval (CI) [2.47, 6.13]), and concentration difficulties, $\chi^2 = 10.84$, $p = .001$, OR = 2.13 (95% CI [1.37, 3.30]). Postural instability was associated with symptom endorsement of trouble remembering, $\chi^2 = 12.08$, $p < .001$, OR = 1.76 (95% CI [1.29, 2.40]). **Conclusions:** Certain post-concussion on-field signs exhibited after injury were associated with specific symptom endorsement within 1 day post injury. Based on these associations, individualized education-based interventions and academic accommodations may help reduce unanticipated worry from parents, students, and teachers following a student-athlete's sport-related concussion, especially in cases of delayed onset symptoms. (*JINS*, 2018, *24*, 476–485)

Keywords: Mild traumatic brain injury, Sport-related concussion, Trauma, Sports medicine, Symptoms, Structural equation modeling, Head injuries

INTRODUCTION

Concussion during athletic competition, termed sport-related concussion (SRC), is a form of mild traumatic brain injury (mTBI) induced by biomechanical forces that triggers a pathophysiological process resulting in functional derangements, typically in the absence of abnormal neuroradiographic correlates (McCrory et al., 2017). Compared to the general population, athletes participating in contact or collision sports are more likely to experience concussion (Coronado, McGuire, Faul, Sugerman, & Pearson, 2012; Gessel, Fields, Collins, Dick, & Comstock, 2007; McCrory et al., 2017; Tator et al., 2016).

Following SRC, immediate, objectively measured signs and subsequent self-reported symptoms should be assessed by a physician or other licensed healthcare provider (Belanger & Vanderploeg, 2005; Karr, Areshenkoff, & Garcia-Barrera, 2014; McCrory et al., 2013, 2017). These on-field signs often include balance/postural instability (Guskiewicz, Ross, & Marshall, 2001; McCrea et al., 2003), memory (Cantu, 2001; Graham, Rivara, Ford, & Mason Spicer, 2014; McCrory et al., 2017), concentration/working memory (McCrea et al., 2003), and visual tracking/pupil dysfunction (dilatation, non-reactive to light, unequal size, convergence insufficiency, etc.; McCrea, Kelly, Kluge, Ackley, & Randolph, 1997; Mucha et al., 2014; Wojtys et al., 1999).

During recovery, individual symptoms and their severity are monitored *via* self-reported indices such as the Symptom Scale from the Sport Concussion Assessment Tool

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Table 1. On-field signs and symptom cluster

	On-field signs[a]
Postural instability[c]	(a) maintain posture in single leg, double leg, and tandem stances
Working memory/ concentration[d]	(a) repeat strings of number digits; (b) list days of the week backward
Pupillary dysfunction[e]	(a) atypical pupil functioning in any form (e.g., dilation, absence of light reactivity, unequal size); (b) or oculomotor dysfunction
Immediate memory[f]	(a) Repeat three words (b) Delayed recall of three words
	Symptom clusters[b]
Cognitive-migraine-fatigue	Headache, dizziness, fatigue, drowsiness, sensitivity to light, sensitivity to noise, feeling slowed down, mentally foggy, difficulty concentrating, difficulty remembering
Somatic	Vomiting, numbness

[a]Adapted from the SCAT3.
[b]Derived from Kontos et al., 2012.
[c]Postural instability consisted of three Modified Balance Error Scoring System (M-BESS; Hunt, Ferrara, Bornstein, & Baumgartner, 2009) trials. Positions listed were recorded as a fail if a single major loss of balance occurred during the 20-s period.
[d]Working memory/concentration was based on whether athletes were able to successfully state the days of the week backward. Performance on days of the week backward was recorded as a fail if they were unable to state the entire sequence correctly. Working memory/ concentration also consisted of the portion of the SCAT3 that involves repeating strings of digits backward. Digits backward were coded as a fail if they inaccurately recited one of the two the strings (two and three numbers for consecutive strings).
[e]Visual tracking and pupil abnormality (abnormal constriction/dilation, non-reactive to light, unequal size, convergence insufficiency) was recorded as a fail if any qualitative abnormality was observed.
[f]Immediate memory was characterized by an athlete's ability to repeat three words for encoding and later spontaneously recall the words. Should athletes not be able to repeat or recall all three words, their performance was recorded as a fail.

(SCAT; McCrory et al., 2017). SRC symptoms have been empirically analyzed to yield four primary symptom clusters: (1) cognitive-migraine-fatigue (CMF), (2) affective, (3) somatic, and (4) sleep (Table 1; Kontos et al., 2012).

Preliminary research has shown provisional associations between on-field signs and symptoms in the acute phase post injury. One study of 78 concussed high school and collegiate athletes demonstrated that on-field amnesia was significantly associated with reduced neuropsychological scores and increased total symptom scores at 2 days post injury (Collins et al., 2003). Pearce and colleagues (2015) showed that student-athletes who experienced oculomotor (convergence insufficiency) and cognitive impairment reported significantly greater total symptom scores than those who did not within the first 10 days post-injury (Pearce et al., 2015). Moreover, objectively measured signs have also been linked to specific self-reported symptom patterns. A study of 138 male high school football players suggested that those with greater cognitive deficits (i.e., memory and reaction time) were more likely to endorse posttraumatic migraines during the initial course of recovery between 1 and 7 days (Kontos et al., 2013).

Structural equation modeling (SEM) is a statistical method well suited to study associations between signs and symptoms after SRC due to its capacity to examine complex networks of multiple constructs. Using SEM, the aim of the current study was to investigate the relationship between immediate, objective on-field signs and self-reported symptoms during the first day post injury in a sample of high school athletes who sustained a SRC. Due to the limited opportunity for athletes to experience certain symptoms during the first day of recovery (i.e., sleep and affective clusters), the current study examined symptom endorsement in two of the four previously mentioned clusters: (1) CMF and (2) somatic.

Several previous studies formed the basis for our empirically-driven hypotheses. First, due to the previously demonstrated relationship between verbal memory scores and CMF cluster symptoms (Broglio, Sosnoff, & Ferrara, 2009; Kontos et al., 2013), it was hypothesized that athletes' on-field immediate memory would be associated with the CMF cluster. Additionally, based on the previously demonstrated relationship between memory functioning (i.e., posttraumatic amnesia) and total symptom scores (Collins et al., 2003), it was hypothesized that immediate memory would also be significantly associated with the somatic cluster. Second, due to an expected relationship with subjectively reported CMF symptoms and objectively measured cognitive performance, it was hypothesized that on-field working memory/concentration deficits would be associated with the self-reported symptoms in the CMF cluster, which is also supported by studies investigating dual task paradigms (Howell, Osternig, & Chou, 2015).

Third, a relationship between postural instability and the CMF cluster was hypothesized due to a previously demonstrated association between objectively measured postural stability and cognitive measures of working memory. Specifically, Guskiewicz et al. (2001) showed that athletes exhibiting postural instability also demonstrated poorer working memory performance (Trail-Making Test B and Wechsler Digit Span Test Backward) at day 1 post injury. This relationship is further supported by prior studies documenting the relationship between objective and subjective measures of balance within 48 hr of concussion (Broglio et al., 2009). Fourth, visual tracking/ pupillary dysfunction was thought to predict increased CMF cluster endorsement based on previously demonstrated associations between vestibulo-ocular dysfunction and dizziness and concentration difficulties (Ellis et al., 2017).

METHODS

Participants and Setting

The sample included 237 concussed, student-athletes participating in a variety of sports in the southeastern United States (Table 2). Inclusion criteria were: (a) SRC diagnosed

Table 2. Demographics

Sex	*N* (%)
Male	175 (73.8)
Female	62 (26.2)
Injury setting	
Game	184 (77.6)
Practice	45 (19.0)
Other	8 (3.4)
Concussion history	
No	172 (72.6)
Yes	65 (27.4)
Sport	
Football	95 (40.1)
Soccer	53 (22.4)
Wrestling	23 (9.7)
Basketball	21 (8.9)
Lacrosse	7 (3.0)
Softball	10 (3.7)
Volleyball	5 (2.1)
Baseball	4 (1.7)
Cheerleading	3 (1.3)
Track and field	2 (0.8)
Other	2 (0.8)
Golf	1 (0.4)
Tennis	1 (0.4)
Ultimate frisbee	1 (0.4)

Note. Number and percentages of recorded demographics.

by a certified athletic trainer (ATC) and confirmed by team physician based on the international Concussion In Sport Group guidelines (CISG4; McCrory et al., 2013), (b) sign and symptom documentation within the first 24 hr post injury, (c) high school athlete ages 13 to 18, and (d) English speaking. All athletes not meeting these criteria were excluded from analysis.

Of the 237 who met criteria for inclusion in the study, 175 (73.8%) were male and 65 (27.4%) reported a prior history of concussion. Objective signs were evaluated at the time of injury or immediately after the participating game or practice (i.e., in the locker room). Symptoms were recorded by the ATC within 24 hr of the injury and entered into an institutional database. Injuries occurred either during a game (184; 77.6%), practice (45; 19.0%), or other (e.g., weight room, school, etc.; 8; 3.4%). Data included in this manuscript were obtained in compliance with the Helsinki Declaration and Institutional Review Board approval was obtained for the purpose of the study (108202017190522).

Materials

On-field signs, which were based on interpretations of test responses/ results, were derived from the SCAT3 assessment (McCrory et al., 2013) and adapted for ease of rapid on-field administration. The constructs assessed included; (1) immediate memory, (2) balance, and (3) concentration/ working memory (Table 1). Additionally, consistent with the National Athletic Trainers' Association Position Statement on the management of SRC, (4) visual tracking and pupil abnormality (abnormal constriction/dilation, non-reactive to light, unequal size, convergence insufficiency, etc.) was included and assessed as an observed on-field sign (Broglio et al., 2014; Guskiewicz et al., 2004). Immediate memory was characterized by an athlete's ability to repeat three words for encoding and later spontaneously recall the words. Athletes were administered one trial per task and should athletes not be able to repeat and recall all three words in a single trial, their performance was recorded as a fail.

Also derived and adapted from the SCAT3, working memory/ concentration was based on whether athletes were able to successfully state the days of the week backward. Performance on days of the week backward was recorded as a fail if they were unable to state the entire sequence correctly in one trial. Working memory/ concentration also consisted of adapted trials of the SCAT3 that involves repeating strings of digits backward. The digits backward component included two trials, the first with two numbers and the second with three numbers. Digits backward was coded as a fail if athletes were unable to successfully complete both trials. Postural stability consisted of three mBESS positions (i.e., single, double, and tandem stances) and was recorded as a fail if a single major loss of balance occurred during the 20-s period for each position.

To assess self-reported symptoms, the Symptom Scale from the SCAT3 was used (McCrory et al., 2013). The SCAT3 Symptom Scale is comprised of 22 symptoms commonly associated with concussion, each of which is rated on a 0–6 Likert scale, with 0 = none and 6 = severe. The 22 symptoms have previously been factor analyzed and classified into four primary postconcussion symptom categories (viz., clusters). These four clusters include: (1) CMF, (2) affective, (3) somatic, and (4) sleep (Kontos et al., 2012). As stated above, only the CMF and somatic symptom clusters were included as outcomes for the current study. Given that the presence or absence of a symptom (binary variable) was of primary interest, student-athlete responses were coded as "No" with a value of 0, and "Yes" for a value of 1 or greater. The number of endorsed symptoms within a particular cluster was included as the dependent variable.

Statistical Analysis

A two-step SEM analysis was performed (Anderson & Garbing, 1988). First, the measurement model was estimated using the maximum likelihood method and evaluated based on a chi-square test and several other fit indices, which included comparative fit index (CFI), standardized root-mean-square residual (SRMR), root-mean-square error of approximation (RMSEA), and normed fit index (NFI). To examine the factor structures, confirmatory factor analysis (CFA) was used to test the measurement model by examining the relationship between individual measured signs (e.g., single leg stance) and the constructs/latent variables that represent them (e.g., postural instability).

Second, the full proposed structural model that examines the relationship between signs and self-reported symptoms was estimated using a similar process described above. For instances in which on-field signs were significantly predictive of symptom clusters, follow-up binary logistic regression analyses were performed to further examine the relationship between on-field signs and specific self-reported symptoms in significant clusters. All analyses were performed using the computer software LISREL Version 9 (Fleishman & Benson, 1987) and Statistical Package for the Social Sciences (SPSS Statistics 24.0).

RESULTS

Gender, sport, concussion history, and injury setting (practice or game) of the 237 subjects are provided in Table 2. The most commonly observed on-field sign following SRC was the inability to recite strings of numbers backward ($N = 84$; 35.4%) and the more frequently endorsed symptoms were from the CMF cluster ($M = 3.1$; $SD = 1.97$). The frequency and percentages of student-athletes exhibiting failed trials of each on-field sign is presented in Table 3. Gender differences were not observed in the endorsement of CMF, $t = 0.75$, $p = .94$, or somatic symptom clusters, $t = -0.52$, $p = .61$. Gender differences were also not observed on pupil and postural instability signs, including pupil/ ocular dysfunction, $\chi^2 = 0.49$, $p = .49$, double leg stance, $\chi^2 = 0.61$, $p = .43$, single leg stance, $\chi^2 = 0.07$, $p = .79$, and tandem stance, $\chi^2 = 0.07$, $p = .79$. Furthermore, gender differences were not observed in working memory and immediate memory signs, including days backward, $\chi^2 = 0.02$, $p = .90$, numbers backward, $\chi^2 = 0.0$, $p = .99$, repeat words, $\chi^2 = 0.37$, $p = .54$, and remember words, $\chi^2 = 0.87$, $p = .35$.

Measurement Model

Fit indices and parameter estimates from the CFA indicated a very good fit of the measurement model (Table 4). All pattern coefficients of observed variables (e.g., single leg stance) were significant, indicating that measured on-field indicators were significantly associated with their corresponding latent variables (e.g., postural instability). Coefficients for latent variables/ constructs fell above the acceptable cutoff (0.70; Hair, Anderson, Tatham, & Black, 1998), ranging from 0.74 to 0.81 (postural instability), 0.72 to 0.75 (immediate memory), and 0.79 to 0.84 (concentration/ working memory). A correlation matrix displaying relationships between the variables is provided in Table 3.

Table 4. Fit indices for proposed measurement and structural models

	χ^2	CFI	NFI	SRMR	RMSEA
Measurement model df = 23, 237)	38.82 ($p = .02$)	0.97	0.94	0.01	0.05 [0.2, 0.08][a]
Structural model (df = 27, 237)	48.35 ($p = .01$)	0.96	0.92	0.02	0.05 [0.02, 0.10][a]

Note. Values suggesting good fit for the model have previously been proposed as comparative fit index (CFI > 0.95), normed fit index (NFI > .90), root-mean-square error of approximation (RMSEA ≤ 0.06), and standardized root-mean-square residual (SRMR ≤ 0.08; Byrne, 1994; Hu & Bentler, 1999)
[a]95% CI.

Goodness of fit of the measurement and structural model was based on acceptable values, including the CFI (> 0.95), NFI (> .90), RMSEA (≤ 0.06), and SRMR (≤ 0.08; Byrne, 1994; Hu & Bentler, 1999). Fit indices indicated an acceptable fit of the measurement model $\chi^2(23,237) = 38.82$, $p = .02$; CFI = 0.97; NFI = 0.94; RMSEA = 0.05 (95% CI [0.02, 0.08]); SRMR = 0.01.

Structural Model

To test the proposed structural model, or relationship between signs and two self-reported symptom clusters, the two symptom clusters were added to the measurement model. Initial paths from latent on-field signs to designated symptom clusters were added based on hypotheses described above. The structural model demonstrated a good fit to the data, $\chi^2(27,237) = 48.35$, $p = .01$; CFI = 0.96; NFI = 0.92; RMSEA = 0.05 (95% CI [0.02, 0.10]); SRMR = 0.02 (Table 4; Figure 1).

Table 3. Correlation matrix of signs and symptoms

Cognitive-migraine-fatigue[a]	3.1 (1.97)	1.0									
Somatic[a]	0.08 (0.29)	0.17	1.0								
Pupil dysfunction[b]	16 (6.8%)	0.03	0.02	1.0							
Double leg stability[b]	21 (12.2%)	0.25	0.22	0.03	1.0						
Single leg stability[b]	47 (19.8%)	0.24	0.08	0.08	0.59	1.0					
Tandem stance stability[b]	29 (12.2%)	0.15	0.08	0.05	0.61	0.65	1.0				
Repeat words[b]	27 (11.4%)	0.19	0.09	0.06	0.17	0.16	0.19	1.0			
Repeat days backward[b]	51 (21.5%)	0.22	0.01	0.06	0.05	0.02	0.06	0.36	1.0		
Repeat numbers backward[b]	84 (35.4%)	0.22	0.04	0.08	0.14	0.05	0.10	0.32	0.66	1.0	
Remember repeated words[b]	66 (27.8%)	0.30	0.04	0.02	0.01	0.21	0.17	0.55	0.29	0.29	1.0

Note. Correlation table demonstrating relationships (Pearson correlation) of all the included variables in the model.
[a]Number of symptoms endorsed within each cluster; presented as mean and standard deviation.
[b]Number and percentage of athletes exhibiting a failed performance of each on-field sign.

https://doi.org/10.1017/S1355617717001321 Published online by Cambridge University Press

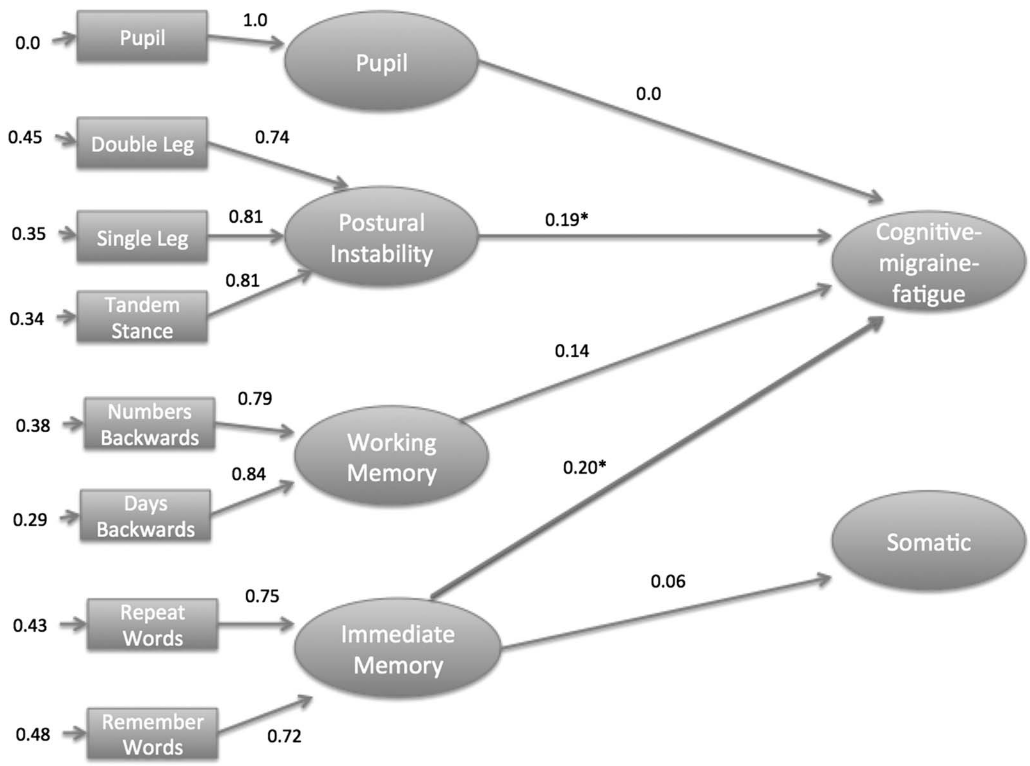

Fig. 1. Final structural model of signs and symptoms.

Significant Predictors in Final Model

Two paths from on-field signs to self-reported symptom clusters during the first day post injury were significant. Immediate memory, $\beta = 0.20$, $p = .04$ and postural instability, $\beta = 0.19$, $p < .01$, significantly predicted a greater likelihood of student-athletes endorsing symptoms in the CMF cluster (Table 5). Follow-up bivariate regression analyses of the significant on-field signs and individual symptoms in the CMF cluster were also significant for particular symptoms (Table 6). Bonferroni corrected alpha levels were set at 0.0025 to control for inflated type-I error associated with multiple comparisons.

Immediate memory was significantly associated with student-athletes' reporting of trouble remembering, $\chi^2 = 37.92$, $p < .001$, odds ratio (OR) = 3.89 (95% confidence interval (CI) [2.47, 6.13]), and concentration difficulties, $\chi^2 = 10.84$, $p = .001$, OR = 2.13 (95% CI [1.37, 3.30]). Postural instability was significantly associated with student-athletes' reporting of trouble remembering, $\chi^2 = 12.08$, $p < .001$, OR = 1.76 (95% CI [1.29, 2.40]).

Table 5. Standardized coefficients for the structural model

	Pupillary dysfunction	Postural instability	Immediate memory	Concentration/ working memory
Cognitive-migraine-fatigue	0.0	0.19[a]	0.20[b]	0.14
Somatic	*	*	0.06	*

[a]Paths significant at the $p > .05$ level.
[b]Paths significant at the $p > .01$ level.
*Paths not analyzed within the model.

Non-significant Predictors in Final Model

Multiple paths in the proposed structural model did not achieve statistical significance and indicated that certain on-field signs did not effectively predict the likelihood of reporting particular symptoms within the first day post injury. For instance, the occurrence of visual tracking/pupillary dysfunction, $\beta = 0.00$, $p = .95$, and working memory/concentration, $\beta = 0.14$, $p = .11$ during on-field evaluation, as assessed in the current study, did not increase the likelihood of high school athletes endorsing CMF-related symptoms following SRC. Furthermore, immediate memory difficulties did not predict a greater likelihood of reporting symptoms in the somatic cluster, $\beta = 0.06$, $p = .41$.

DISCUSSION

The current study examined whether on-field signs immediately following injury could accurately predict student-athletes' symptom reporting within 1 day following SRC. In a sample of 237 concussed student-athletes, immediate memory was significantly associated with the subsequent self-reported symptoms of trouble remembering and concentration difficulties. Furthermore, postural instability at the time of the concussion was significantly associated with subsequent self-reported symptoms of trouble remembering.

https://doi.org/10.1017/S1355617717001321 Published online by Cambridge University Press

Table 6. Individual symptoms of significant on-field signs and cluster

	$\chi^{2,a}$	B^{b}	p-Value[c]	OR	95% CI lower[d]	95% CI upper[e]
Immediate memory						
Headache	0.75	0.30	.408	*	*	*
Dizziness	8.03	0.63	.008	*	*	*
Photophobia	2.97	0.36	.081	*	*	*
Trouble remembering*	37.92	1.36	<.001	3.89	2.47	6.13
Fatigue	1.10	0.26	.285	*	*	*
Phonophobia	0.13	0.10	.721	*	*	*
Feeling slowed	0.01	0.02	.927	*	*	*
Drowsy	6.58	0.66	.008	*	*	*
Foggy	4.84	0.45	.027	*	*	*
Trouble concentrating*	10.84	0.75	.001	2.13	1.37	3.30
Postural instability						
Headache	0.68	0.22	.439	*	*	*
Dizziness	10.40	0.59	.004	*	*	*
Photophobia	0.34	0.09	.556	*	*	*
Trouble remembering*	12.08	0.56	<.001	1.76	1.29	2.40
Fatigue	1.38	0.21	.226	*	*	*
Phonophobia	0.01	0.02	.916	*	*	*
Feeling slowed	3.93	0.36	.039	*	*	*
Drowsy	7.67	0.522	.004	*	*	*
Foggy	4.15	0.32	.039	*	*	*
Trouble concentrating	3.26	0.32	.061	*	*	*

Note. Bivariate regression analyses of significant on-field signs and symptoms in cognitive-migraine-fatigue cluster.
[a]Chi-squared statistic of bivariate regressions.
[b]Standardized beta regression weights.
[c]Bonferroni corrected alpha level controlling for multiple comparisons set at 0.0025.
[d]Lower bound 95% CI of OR.
[e]Upper bound 95% CI of OR.
*Significant at the Bonferroni corrected alpha level of 0.0025.

Significant Associations

Immediate memory at the time of injury was associated with the CMF symptom cluster (e.g., trouble remembering and difficulty concentrating). The association of these specific signs and symptoms is similar to a previous study of 32 concussed collegiate athletes. At 48 hr following injury, a relationship between objectively measured memory (i.e., ImPACT verbal memory score) and symptom endorsement of difficulty remembering and/or concentrating was demonstrated (Broglio et al., 2009).

While changes in cognition are likely associated with the metabolic demands following SRC (Giza & Hovda, 2014; Yoshino, Hovda, Kawamata, Katayama, & Becker, 1991), the exact physiological mechanism is not fully understood. Prior functional magnetic resonance imaging studies suggest that neurotransmitter and synaptic alterations may be the mechanism driving changes in cognition during the acute phase of recovery. For example, reduced task-related blood oxygen level dependent signaling has previously been associated with poorer performance on a task of attention/working memory in high school athletes acutely following SRC (Keightley et al., 2014). Given the relationship between memory performance and cognitive symptoms, these results suggest that altered neurotransmission may begin as quickly as minutes after injury and persist further during the acute phase of recovery (McCrea et al., 2003).

Measured postural instability also increased a student-athlete's likelihood of reporting CMF-related symptoms. Specifically, postural instability was associated with an increased likelihood of self-reported trouble remembering during the first day post-injury. The relationship between postural instability and cognitive-related self-reported symptoms (i.e., trouble remembering) is highlighted through studies assessing SRC with a dual-task paradigm (Lee, Sullivan, & Schneiders, 2013). In a study of 10 concussed individuals, the inclusion of a divided attention component in a dual-task gait balance test was a more sensitive measure of balance than a single gait balance task within 48 hr post-injury (Parker, Osternig, Lee, Donkelaar, & Chou, 2005).

As highlighted above, the energy crisis and hypometabolism of glucose may be the mutual mechanism driving the association between postural instability at the time of injury and self-reported memory difficulties 1 day later. While not yet directly demonstrated in mTBI or concussion, previous research in the area of moderate and severe TBI has shown a disproportional acute hypometabolism in the frontal and temporal lobes (Wright et al., 2013), two regions associated with postural instability (executive functions of attention and concentration on balance task; Reilly, van Donkelaar,

https://doi.org/10.1017/S1355617717001321 Published online by Cambridge University Press

Saavedra, & Woollacott, 2008) and memory (Squire & Zola-Morgan, 1991).

Within the same study, this acute hypometabolism was significantly associated with later measured atrophy in the same regions and more distal attention, executive function, and psychomotor deficits. While mTBI is unlikely to result in long-term atrophy and permanent cognitive impairments (Giza & Hovda, 2014), the higher levels of frontal-temporal hypometabolism seen in severe TBI may exist to a lesser extent in mTBI, with a return to physiologic and neurologic homeostasis and without irreversible cellular changes such as protease activation and altered cytoskeletal proteins.

Non-significant Associations

Results did not support the hypothesized relationship between immediate memory and the somatic symptom cluster. Other previous studies suggesting this potential relationship included athletes who suffered from a more severe memory condition (i.e., posttraumatic amnesia), which may account for the absence of the expected relationship observed in the current result (Collins et al., 2003). Furthermore, results failed to show an association between working memory/ concentration and self-reported CMF symptoms. The lack of relationship between the two in the current study was unexpected, considering the significant correlation between subjective cognitive-related symptom reporting and objective neurocognitive measures reported in the study of 32 concussed collegiate athletes by Broglio and colleagues (2009).

Furthermore, in contrast to Ellis et al. (2017), the current study failed to demonstrate an association between visual tracking/ pupillary dysfunction and CMF symptoms. The positive association, as compared to the null findings in the current study, may be attributable to differences in study methodologies. Specifically, Ellis et al. (2017) involved a neurosurgeon performing a comprehensive vestibulo-ocular exam in an office setting, whereas the current study used a general screening of pupil/ocular motor dysfunction by an ATC on the field. The discrepancy between studies may have been reduced with consistent use of a vestibular and ocular impairment measure, such as the Vestibular/Ocular Motor Screening assessment, which is becoming a standard instrument in the SRC research field.

Clinical Utility of the Model

Clarifying the relationship between measured on-field signs and symptom reporting has potential to improve SRC management (Graham et al., 2014). This is especially true when considering underreporting by student athletes (Guskiewicz et al., 2004; Kuhn et al., 2017). A clinician's confidence in making an initial diagnosis is bolstered when discrepancy exists between concerning signs without symptom endorsement, which an athlete may choose to conceal. Furthermore, using objective signs to predict immediate symptoms can be of use in the case of delayed symptom onset (Duhaime et al., 2012; McCrory et al., 2017). In one study of 450 collegiate athletes wearing Head Impact Telemetry technology, half of the 48 diagnosed concussions had delayed or unclear timing of symptom onset (Duhaime et al., 2012). Observed on-field signs can preemptively alert parents and coaches to potential symptoms that are more likely to occur, should there be a delayed onset.

While treatment guidelines for the initial day of recovery are often limited and involve primarily rest (McCrory et al., 2017), the associations between immediate signs and symptoms have implications for individualized, preventative education-based interventions. Education of coaches and parents, which has been recommended strongly through several position statements (Broglio et al., 2014; Echemendia et al., 2012; Halstead, Walter, & Council on Sports Medicine and Fitness, 2010; Harmon et al., 2013; McCrory et al., 2013), can be individualized based on the specific signs and symptoms observed and may potentially reduce symptoms, psychological distress, and disruption of social activities.

For example, in separate studies of adolescents and adults in the general population, individuals who received an informational booklet on common symptoms following head injury with suggested coping strategies reported fewer symptoms and experienced less psychological distress at 3 months follow-up (Ponsford et al., 2001, 2002). Furthermore, parental education by providers who may be able to predict future symptoms from documented signs at the time of injury can aid in easing potential family distress, as parents and caregivers may be able to anticipate and expect the occurrence of specific symptoms, as opposed to being surprised and alarmed by them. Given that mTBI in children in the general population has been shown to increase family distress (Ganesalingam et al., 2008), more specific parental counseling may allay family concerns and foster a healing home environment.

These results may also have implications for individualized return-to-school interventions. In a recent study conducted by Ransom et al. (2015), symptomatic students who returned to school following SRC reported higher levels of concern for injury-related adverse effects on learning, school performance, and increased school problems. Parents exhibited similarly heightened anxiety. Prophylactic individualized education-based reassurance can be provided to students and parents early in the recovery process to alleviate concerns related to learning and school performance. For instance, should the student exhibit immediate memory difficulties and postural instability at injury, parents and students can be provided education and reassured about subsequent memory and concentration difficulties that may likely ensue. With this knowledge, symptom-specific academic accommodations can be arranged in advance of the student's return to the learning environment (Gioia, 2016).

Future Directions

Logical follow-up to this study would include extending the current findings to assess longitudinal recovery and outcomes beyond the 1-day timeframe. Additionally, although this study included a diverse set of on-field signs as variables of

https://doi.org/10.1017/S1355617717001321 Published online by Cambridge University Press

interest, there is a wide array of on-field signs that can be used in the detection and management of SRC (e.g., orientation, coordination, etc.). Future studies should seek to replicate the associations demonstrated in the current study, while integrating additional on-field signs that are commonly assessed. Our knowledge of associations between on-field signs and symptoms would improve with prospective studies examining the current findings throughout the duration of recovery. For example, future studies should examine if the relationship between on-field signs and symptoms remains significant at days 3, 7, and furthermore, until full recovery is reached.

Limitations

This study is not without limitations. In particular, we were not able to control for many modifying factors previously shown to influence recovery from SRC and symptom reporting, such as a diagnosis of learning disorder/attention deficit hyperactivity disorder (Bonfield, Lam, Lin, & Greene, 2013; Iverson, Atkins, Zafonte, & Berkner, 2016; Zuckerman, Lee, Odom, Solomon, & Sills, 2013), history of treatment of depression and/ or anxiety (Iverson et al., 2015; Yengo-Kahn & Solomon, 2015), history of previous concussion (Guskiewicz et al., 2004; McCrea et al., 2003), etc. Future research should attempt to replicate the current findings, while also examining these modifying factors as potential mediators of signs and symptoms.

Furthermore, although signs were objectively measured and assessed, items such as the mBESS stances did involve some subjective interpretation from ATCs, requiring them to individually gauge a "single major loss of balance." While this was not codified operationally, it was performed by the same trainers, maintaining consistency in the rating. Further work should look to advance the findings of the current study through the inclusion of baseline measures and comparative post injury performances. Additionally, the current cohort was drawn from a southeastern geographical region, which may not be generalizable to other areas of the country or to international groups.

Conclusions

The current study examined whether on-field signs assessed immediately following injury could accurately predict student-athlete symptom reporting at 1 day following SRC in a sample of 237 concussed student-athletes. Findings indicated that immediate memory difficulties were significantly associated with the subsequent increased symptom reporting of trouble remembering and concentration difficulties. Postural instability at the time of the concussion was significantly associated with increased symptom reporting of trouble remembering. Through increased awareness of these associations, prophylactic management of SRC consisting of multimodal education-based interventions can be implemented based on anticipated symptoms from on field-signs that are observed immediately following SRC.

ACKNOWLEDGMENTS

Mr. Brett, Mr. Kuhn, and Drs. Yengo-Kahn, Jeckell, and Zuckerman report no conflicts of interest. Dr. Solomon is a consultant for the Nashville Predators, Tennessee Titans, and the athletic departments of Tennessee Tech University and the University of Tennessee, fees paid to institution. He is also a consultant to the National Football League Department of Health and Safety. No contents of this work have been previously presented. No grants or outside funding supported this work.

REFERENCES

Anderson, J.C., & Garbing, D.W. (1988). Structural equation modeling in practice: A review and recommended two-step approach. *Psychological Bulletin*, *103*(3), 411–423.

Belanger, H.G., & Vanderploeg, R.D. (2005). The neuropsychological impact of sports-related concussion: A meta-analysis. *Journal of the International Neuropsychological Society*, *11*(4), 345–357.

Bonfield, C.M., Lam, S., Lin, Y., & Greene, S. (2013). The impact of attention deficit hyperactivity disorder on recovery from mild traumatic brain injury. *Journal of Neurosurgery. Pediatrics*, *12* (2), 97–102. doi: 10.3171/2013.5.PEDS12424

Broglio, S.P., Cantu, R.C., Gioia, G.A., Guskiewicz, K.M., Kutcher, J., & Palm, M., National Athletic Trainer's Association. (2014). National Athletic Trainers' Association position statement: Management of sport concussion. *Journal of Athletic Training*, *49*(2), 245–265. doi: 10.4085/1062-6050-49.1.07

Broglio, S.P., Sosnoff, J.J., & Ferrara, M.S. (2009). The relationship of athlete-reported concussion symptoms and objective measures of neurocognitive function and postural control. *Clinical Journal of Sport Medicine*, *19*(5), 377–382. doi: 10.1097/JSM.0b013e3181b625fe

Byrne, B. (1994). *Structural equation modeling with EQS and EQS/Windows*. Thousand Oaks, CA: Sage.

Cantu, R.C. (2001). Posttraumatic retrograde and anterograde amnesia: Pathophysiology and implications in grading and safe return to play. *Journal of Athletic Training*, *36*(3), 244–248.

Collins, M.W., Iverson, G.L., Lovell, M.R., McKeag, D.B., Norwig, J., & Maroon, J. (2003). On-field predictors of neuropsychological and symptom deficit following sports-related concussion. *Clinical Journal of Sport Medicine*, *13*(4), 222–229.

Coronado, V.G., McGuire, L.C., Faul, M., Sugerman, D.E., & Pearson, W.S. (2012). Traumaticbrain injury epidemiology and public health issues. In D.I. Zasler, D.E. Katz & R.D. Zafonte (Eds.), *Brain injury medicine: Principles and practice* (pp. 84–100). New York, NY: Demos Medical Publishing.

Duhaime, A.C., Beckwith, J.G., Maerlender, A.C., McAllister, T. W., Crisco, J.J., Duma, S.M., … Greenwald, R.M. (2012). Spectrum of acute clinical characteristics of diagnosed concussions in college athletes wearing instrumented helmets: Clinical article. *Journal of Neurosurgery*, *117*(6), 1092–1099. doi: 10.3171/2012.8.JNS112298

Echemendia, R.J., Iverson, G.L., McCrea, M., Broshek, D.K., Gioia, G.A., Sautter, S.W., … Barr, W.B. (2012). Role of neuropsychologists in the evaluation and management of sport-related concussion: An inter-organization position statement. *Archives of Clinical Neuropsychology*, *27*(1), 119–122. doi: 10.1093/arclin/acr077

Ellis, M.J., Cordingley, D.M., Vis, S., Reimer, K.M., Leiter, J., & Russell, K. (2017). Clinical predictors of vestibulo-ocular dysfunction in pediatric sports-related concussion. *Journal of Neurosurgery. Pediatrics*, *19*(1), 38–45. doi: 10.3171/2016.7.PEDS16310

Fleishman, J., & Benson, J. (1987). Using LISREL to evaluate measurement models and scale reliability. *Educational and Psychological Measurement*, *47*(4), 925.

Ganesalingam, K., Yeates, K.O., Ginn, M.S., Taylor, H.G., Dietrich, A., Nuss, K., & Wright, M. (2008). Family burden and parental distress following mild traumatic brain injury in children and its relationship to post-concussive symptoms. *Journal of Pediatric Psychology*, *33*(6), 621–629. doi: 10.1093/jpepsy/jsm133

Gessel, L., Fields, S., Collins, C., Dick, R., & Comstock, R. (2007). Concussions among United States high school and collegiate athletes. *Journal of Athletic Training*, *42*(4), 495–503.

Gioia, G.A. (2016). Medical-school partnership in guiding return to school following mild traumatic brain injury in youth. *Journal of Child Neurology*, *31*(1), 93–108. doi: 10.1177/0883073814555604

Giza, C.C., & Hovda, D.A. (2014). The new neurometabolic cascade of concussion. *Neurosurgery*, *75*(Suppl 4), S24–S33. doi: 10.1227/NEU.0000000000000505

Graham, R., Rivara, F., Ford, M., & Mason Spicer, C. (2014). *Sports-related concussions in youth: Improving the science, changing the culture*. Washington, DC: National Academies Press.

Guskiewicz, K.M., Bruce, S.L., Cantu, R.C., Ferrara, M.S., Kelly, J.P., McCrea, M., … Valovich McLeod, T.C. (2004). National Athletic Trainers' Association Position Statement: Management of sport-related concussion. *Journal of Athletic Training*, *39*(3), 280–297.

Guskiewicz, K.M., Ross, S.E., & Marshall, S.W. (2001). Postural stability and neuropsychological deficits after concussion in collegiate athletes. *Journal of Athletic Training*, *36*(3), 263–273.

Hair, J., Anderson, R., Tatham, R., & Black, W. (1998). *Multivariate data analysis* (5th ed.), London: Prentice Hall International.

Halstead, M.E., & Walter, K.D., Council on Sports Medicine and Fitness. (2010). American Academy of Pediatrics. Clinical report–Sport-related concussion in children and adolescents. *Pediatrics*, *126*(3), 597–615. doi: 10.1542/peds.2010-2005

Harmon, K.G., Drezner, J.A., Gammons, M., Guskiewicz, K.M., Halstead, M., Herring, S.A., … Roberts, W.O. (2013). American Medical Society for Sports Medicine position statement: Concussion in sport. *British Journal of Sports Medicine*, *47*(1), 15–26. doi: 10.1136/bjsports-2012-091941

Howell, D.R., Osternig, L.R., & Chou, L.S. (2015). Return to activity after concussion affects dual-task gait balance control recovery. *Medicine and Science in Sports and Exercise*, *47*(4), 673–680. doi: 10.1249/MSS.0000000000000462

Hu, L.T., & Bentler, P.M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling*, *6*, 1–55.

Hunt, T.N., Ferrara, M.S., Bornstein, R.A., & Baumgartner, T.A. (2009). The reliability of the modified Balance Error Scoring System. *The Clinical Journal of Sports Medicine*, *19*, 471–475.

Iverson, G.L., Atkins, J.E., Zafonte, R., & Berkner, P.D. (2016). Concussion history in adolescent athletes with attention-deficit hyperactivity disorder. *Journal of Neurotrauma*, *33*(23), 2077–2080. doi: 10.1089/neu.2014.3424

Iverson, G.L., Silverberg, N.D., Mannix, R., Maxwell, B.A., Atkins, J.E., Zafonte, R., & Berkner, P.D. (2015). Factors associated with concussion-like symptom reporting in high school athletes. *JAMA Pediatrics*, *169*(12), 1132–1140. doi: 10.1001/jamapediatrics.2015.2374

Karr, J.E., Areshenkoff, C.N., & Garcia-Barrera, M.A. (2014). The neuropsychological outcomes of concussion: A symptomatic review of meta-analyses on the cognitive sequelae of mild traumatic brain injury. *Neuropsychology*, *28*, 321–336.

Keightley, M.L., Saluja, R.S., Chen, J.K., Gagnon, I., Leonard, G., Petrides, M., & Ptito, A. (2014). A functional magnetic resonance imaging study of working memory in youth after sports-related concussion: Is it still working? *Journal of Neurotrauma*, *31*(5), 437–451. doi: 10.1089/neu.2013.3052

Kontos, A.P., Elbin, R.J., Lau, B., Simensky, S., Freund, B., French, J., & Collins, M.W. (2013). Posttraumatic migraine as a predictor of recovery and cognitive impairment after sport-related concussion. *The American Journal of Sports Medicine*, *41*(7), 1497–1504. doi: 10.1177/0363546513488751

Kontos, A.P., Elbin, R.J., Schatz, P., Covassin, T., Henry, L., Pardini, J., … Collins, M.W. (2012). A revised factor structure for the post-concussion symptom scale: Baseline and postconcussion factors. *The American Journal of Sports Medicine*, *40*(10), 2375–2384. doi: 10.1177/0363546512455400

Kuhn, A., Zuckerman, S., Yengo-Kahn, A., Kerr, Z.Y., Totten, D.J., Rubel, K.E., … Solomon, G.S. (2017). Factors associated with playing through a concussion. *Neurosurgery*, *64*(Suppl 1), 211–216.

Lee, H., Sullivan, S.J., & Schneiders, A.G. (2013). The use of the dual-task paradigm in detecting gait performance deficits following a sports-related concussion: A systematic review and meta-analysis. *Journal of Science and Medicine in Sport*, *16*(1), 2–7. doi: 10.1016/j.jsams.2012.03.013

McCrea, M., Guskiewicz, K.M., Marshall, S.W., Barr, W., Randolph, C., Cantu, R.C., … Kelly, J.P. (2003). Acute effects and recovery time following concussion in collegiate football players: The NCAA Concussion Study. *JAMA*, *290*(19), 2556–2563. doi: 10.1001/jama.290.19.2556

McCrea, M., Kelly, J.P., Kluge, J., Ackley, B., & Randolph, C. (1997). Standardized assessment of concussion in football players. *Neurology*, *48*(3), 586–588.

McCrory, P., Meeuwisse, W., Dvorak, J., Aubry, M., Bailes, J., Broglio, S., … Vos, P.E. (2017). Consensus statement on concussion in sport-the 5(th) international conference on concussion in sport held in Berlin, October 2016. *British Journal of Sports Medicine*. doi: 10.1136/bjsports-2017-097699

McCrory, P., Meeuwisse, W.H., Aubry, M., Cantu, B., Dvorák, J., Echemendia, R.J., … Turner, M. (2013). Consensus statement on concussion in sport: The 4th International Conference on Concussion in Sport held in Zurich, November 2012. *British Journal of Sports Medicine*, *47*(5), 250–258. doi: 10.1136/bjsports-2013-092313

Mucha, A., Collins, M.W., Elbin, R.J., Furman, J.M., Troutman-Enseki, C., DeWolf, R.M., … Kontos, A.P. (2014). A Brief Vestibular/Ocular Motor Screening (VOMS) assessment to evaluate concussions: Preliminary findings. *The American Journal of Sports Medicine*, *42*(10), 2479–2486. doi: 10.1177/0363546514543775

Parker, T.M., Osternig, L.R., Lee, H.J., Donkelaar, P., & Chou, L.S. (2005). The effect of divided attention on gait stability following concussion. *Clinical Biomechanics (Bristol, Avon)*, *20*(4), 389–395. doi: 10.1016/j.clinbiomech.2004.12.004

Pearce, K.L., Sufrinko, A., Lau, B.C., Henry, L., Collins, M.W., & Kontos, A.P. (2015). Near point of convergence after a sport-related concussion: Measurement reliability and relationship to neurocognitive impairment and symptoms. *The American Journal of Sports Medicine*, *43*(12), 3055–3061. doi: 10.1177/0363546515606430

Ponsford, J., Willmott, C., Rothwell, A., Cameron, P., Ayton, G., Nelms, R., … Ng, K. (2001). Impact of early intervention on outcome after mild traumatic brain injury in children. *Pediatrics*, *108*(6), 1297–1303.

Ponsford, J., Willmott, C., Rothwell, A., Cameron, P., Kelly, A.M., Nelms, R., & Curran, C. (2002). Impact of early intervention on outcome following mild head injury in adults. *Journal of Neurology, Neurosurgery, and Psychiatry*, *73*(3), 330–332.

Ransom, D.M., Vaughan, C.G., Pratson, L., Sady, M.D., McGill, C. A., & Gioia, G.A. (2015). Academic effects of concussion in children and adolescents. *Pediatrics*, *135*(6), 1043–1050. doi: 10.1542/peds.2014-3434

Reilly, D.S., van Donkelaar, P., Saavedra, S., & Woollacott, M.H. (2008). Interaction between the development of postural control and the executive function of attention. *Journal of Motor Behavior*, *40*(2), 90–102. doi: 10.3200/JMBR.40.2.90-102

Squire, L.R., & Zola-Morgan, S. (1991). The medial temporal lobe memory system. *Science*, *253*(5026), 1380–1386.

Tator, C.H., Davis, H.S., Dufort, P.A., Tartaglia, M.C., Davis, K.D., Ebraheem, A., & Hiploylee, C. (2016). Postconcussion syndrome: Demographics and predictors in 221 patients. *Journal of Neurosurgery*, *125*(5), 1206–1216. doi: 10.3171/2015.6.JNS15664

Wojtys, E.M., Hovda, D., Landry, G., Boland, A., Lovell, M., McCrea, M., & Minkoff, J. (1999). Current concepts. Concussion in sports. *The American Journal of Sports Medicine*, *27*(5), 676–687. doi: 10.1177/03635465990270052401

Wright, M.J., McArthur, D.L., Alger, J.R., Van Horn, J., Irimia, A., Filippou, M., … Vespa, P. (2013). Early metabolic crisis-related brain atrophy and cognition in traumatic brain injury. *Brain Imaging and Behavior*, *7*(3), 307–315. doi: 10.1007/s11682-013-9231-6

Yengo-Kahn, A.M., & Solomon, G. (2015). Are psychotropic medications associated with differences in baseline neurocognitive assessment scores for young athletes? A pilot study. *The Physician and Sportsmedicine*, *43*(3), 227–235. doi: 10.1080/00913847.2015.1071638

Yoshino, A., Hovda, D.A., Kawamata, T., Katayama, Y., & Becker, D.P. (1991). Dynamic changes in local cerebral glucose utilization following cerebral conclusion in rats: Evidence of a hyper- and subsequent hypometabolic state. *Brain Research*, *561*(1), 106–119.

Zuckerman, S.L., Lee, Y.M., Odom, M.J., Solomon, G.S., & Sills, A.K. (2013). Baseline neurocognitive scores in athletes with attention deficit-spectrum disorders and/or learning disability. *Journal of Neurosurgery. Pediatrics*, *12*(2), 103–109. doi: 10.3171/2013.5.PEDS12524